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Malvern Urban Test Catchment

Volume I

Research Report No. 57

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CANADA-ONTARIO AGREEMENT

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These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Fisheries and Environment Canada, and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

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MALVERN URBAN TEST CATCHMENT

VOLUME I

by

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RESEARCH PROGRAM FOR THE ABATEMENT
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ABSTRACT

An urban test catchment (Malvern), representing a modern residential development of 58 acres, was established and instrumented in Burlington, Ontario. The catchment topography, land use, hydrological characteristics, storm drainage and instrumentation are described and discussed.

A number of precipitation-runoff events were monitored on the catchment in 1973, and some of these events were simulated with the Storm Water Management Model (SWMM) of the U.S. Environmental Protection Agency. A good fit between the simulated runoff hydrographs and the observed hydrographs was obtained.

RÉSUMÉ

Un bassin expérimental de captation en milieu urbain (Malvern), représentant un lotissement résidentiel moderne de 58 acres, a été créé et pourvu d'instruments de contrôle à Burlington (Ontario). On décrit et l'on commente la topographie du bassin de captation, l'utilisation du terrain, les caractéristiques hydrologiques, le réseau d'égouts pluviaux et les appareils utilisés.

Un certain nombre de situations de précipitation et de ruissellement ont fait l'objet d'une étude dans le bassin, en 1973, et quelques-unes de ces situations ont donné lieu à des simulations à l'aide du modèle de gestion des eaux de pluie (Storm Water Management Model) mis au point par l'Environmental Protection Agency des États-Unis. Les hydrogrammes du ruissellement réel correspondaient dans une bonne mesure à ceux obtenus par simulation.

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CONCLUSIONS

The Malvern test catchment, representing a typical modern residential area, is well-suited for urban runoff studies. The catchment is well-defined, and its basic physical characteristics (area, imperviousness, slope) have been fairly accurately determined.

The present catchment instrumentation, consisting of a tipping bucket raingauge, flow measuring weir at the drainage outfall and two automatic samplers, was found suitable for the runoff study. Additional meteorological data were obtained from two raingauges (~2.3 miles away) and a wind monitoring station (3.3 miles away).

When drawing conclusions regarding the runoff simulations with the Runoff Block of the Storm Water Management Model, two limitations must be considered. Firstly, only a limited number (eight) of events have been studied, and secondly, virtually all the runoff originated on the impervious areas. These limitations will be removed as more field data become available.

The runoff volume, peak rate and time to peak were simulated fairly well by a partially calibrated Runoff Block. The representation of the catchment by 10 subcatchments and 21 sewer pipes (15" - 33") allowed a good description of the catchment and of its response. The SWMM default values were found suitable for the Malvern catchment with two possible exceptions - the impervious surface storage was chosen as 0.02 inches rather than 0.06 inches, and no conclusions can be drawn as yet about the infiltration rates, since in the observed events virtually all runoff originated on the impervious areas.

The simulated runoff volumes were underestimated by three percent on average; about two-thirds of all the simulated volumes were within six percent of the observed ones.

The simulated runoff peak flows were underestimated on average by ten percent; about two-thirds of all the simulated flows were within fifteen percent of the observed ones.

The simulated times to peak were on average about equal to the observed ones. Two-thirds of all the simulated times to peak were with five percent of the observed times.

The accuracies of the SWMM simulations given above are better than those reported previously [1, 5, 6] and are likely to follow from the good quality of the Malvern field data used in the SWMM testing. The Runoff Block of the SWMM appears to simulate accurately runoff events on the Malvern catchment for storms of high frequency of occurrence (one to two per month).

RECOMMENDATIONS

The monitoring of urban runoff on the Malvern urban test catchment should be continued and expanded for monitoring of storm water quality.

1 INTRODUCTION

Increasing urbanization of Canadian society makes a dramatic impact on the hydrological cycle in the affected areas. The large imperviousness of urbanized areas contributes to the acceleration and increase of surface runoff, which is typically conveyed by sewers.

At the same time, runoff water, which is rather polluted, is typically discharged into local receiving waters without any treatment. The uncontrolled discharges from combined as well as separate sewers are recognized as one of the major contributors to the lowering of water quality in rivers and lakes. The problem of assessing these sources of pollution and of defining potential solutions for the control of urban runoff has been addressed by the Urban Drainage Subcommittee (UDS) of the Technical Committee for the Canada-Ontario Agreement on Great Lakes Water Quality.

Under the research program of the Urban Drainage Subcommittee, an urgent need for urban runoff data has been identified, and several data collection projects have been initiated. One of these projects, the monitoring and simulation of urban runoff on the Malvern test catchment in Burlington, is described in this report.

The Malvern test catchment is located in a residential area served by separate storm sewers. The catchment has been established, instrumented and monitored by the Hydraulics Research Division of the Canada Centre for Inland Waters in Burlington, Ontario.

The terms of references of this project can be summarized as follows:

1. establish an urban test catchment served by storm sewers;
2. design, install, and operate a data acquisition system monitoring precipitation and runoff quantity; and,
3. simulate selected storm events by the Storm Water Management Model (Runoff Block only).

In the later stages of this project, runoff monitoring and simulation were expanded for the runoff quality aspects. Runoff quality will be dealt with in subsequent volumes.

In this volume, the main stress is on descriptions of the test catchment and the instrumentation. Only a limited number of storms were recorded during the initial stage of the project (1973 data) and these observations are included in the report. Many more events have been recorded in the subsequent years and will be presented in the forthcoming reports.

2 DESCRIPTION OF THE MALVERN URBAN TEST CATCHMENT

The Malvern urban test catchment is a residential subdivision served by separate sewers. The test catchment was instrumented and the data collection started in September, 1973. The data collection season spans from April to November; the instrumentation system becomes inoperational during the winter months. The collection of precipitation/runoff data is expected to continue for at least five years.

2.1 Basic Description of the Urban Area and of the Catchment

The location and drainage boundaries of the Malvern catchment are shown in Figure 1. The total contributing area of the catchment is 57.6 acres, as determined from a map (scale 1"=200 ft) and by field inspection. The catchment is drained by storm sewers.

Basic descriptions of the urbanized area, the City of Burlington and of the test catchment are presented in the format proposed by the University of Florida for the Urban Rainfall/Runoff Data Base, which has been established by the U.S. Environmental Protection Agency. The proposed format appears in Table 1; Table 2 lists the information pertinent to the studied area.

2.2 Catchment Topography

The catchment is gently sloping from the north corner towards the drainage outfall located in the southwest corner (see Figure 1). The highest elevation in the north corner is 295 ft ASL; the lowest elevation in the southwest corner is 272 ft ASL. The average slopes of the drainage area are as follows:

northeast - southwest direction	1.0%
northwest - southeast direction	0.7%
highest elevation point - drainage outlet	1.0%

Local slopes depend on lot gradings. Typically, front yards are sloping towards the street, with slopes varying from 2% to 10%. Backyards are gently sloping (1-3%) away from the street towards drainage swales. Road slopes are on average 1%.

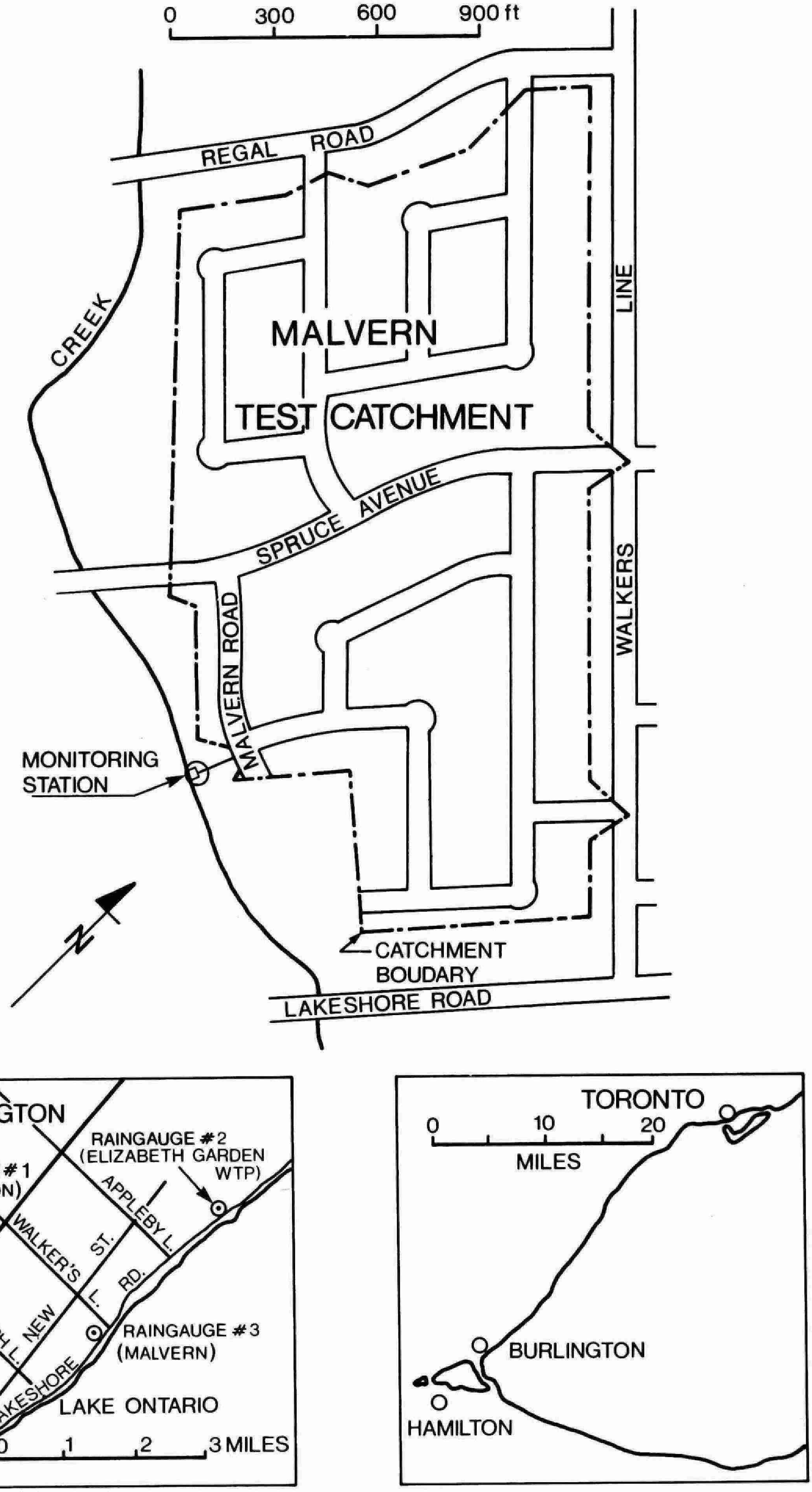

FIGURE 1. MALVERN TEST CATCHMENT - LOCATION MAP

TABLE 1. URBAN RAINFALL/RUNOFF DATA BASE - STORAGE FORMAT PROPOSED BY THE UNIVERSITY OF FLORIDA

A. Master Index File

I INTRODUCTION - four hundred to eight hundred characters

II URBANIZED AREA DESCRIPTION

A. Name - eighty characters
B. Coordinates
   1. Latitude - two fields of two digits, degrees/minute
   2. Longitude - two fields of two digits
C. Area - acres
D. Population - persons and year of census
E. Land Use - % for each of the five categories
F. Sewers - % for each of combined or separate sewers
G. Soils - major soil types
H. Meteorology
   1. Prevalent wind direction for each month
   2. Mean wind speed for each month
   3. Normal monthly temperature ^{o}F
   4. Normal total precipitation per month
   5. Mean evaporation per month
I. Yearly Averages
   1. Prevalent yearly wind direction
   2. Mean wind speed
   3. Average high yearly temperature
   4. Average low yearly temperature
   5. Average yearly temperature
   6. Total yearly precipitation

III. BASIN (CATCHMENT) DESCRIPTION

A. Name - eighty characters
B. Coordinates
   1. Latitude - degrees and minutes
   2. Longitude - degrees and minutes
C. Area - acres
D. Population - persons and year of census
E. Land use - % for each of the five major categories
F. Sewers - % for each of combined or separate sewers
G. Soils - major soil types for the basin
H. Imperviousness
I. Depression storage, pervious and impervious
J. Roughness, pervious and impervious
K. Slope
L. Infiltration parameters
M. Street sweeping frequency
N. Catch basin density

TABLE 1. (CONT'D)

IV. RETRIEVAL CODES

A. State code - two digits
B. City code - four digits
C. Number of events stored - two digits
D. Number of data prints for each event subsection

TABLE 2. URBAN RAINFALL/RUNOFF DATA BASE - MALVERN ROAD, BURLINGTON, ONTARIO

GENERAL INTRODUCTION

Burlington, Ontario: Data collected and reduced by the Hydraulics Research Division, Canada Centre for Inland Waters, rainfall measured by a tipping bucket gauge, flow measured by a weir at the outfall, quality obtained from grab samples collected by an automatic sampler.

URBANIZED AREA DESCRIPTION

Name - Burlington

Location	Degrees	Minutes	Direction
Latitude	43	20	North
Longitude	79	48	West

Area - 21,418 acres 1974 Population - 97,972 persons

	Residential single & multiple	Commercial	Industrial	Open
Land Uses	23.1%	2.3%	3.9%	70.7%

100% Separate Sewers

Major soil types - unclassified

METEOROLOGY

	Winds		Ambient Temperature (^{o}F)	Rainfall (inches)	Evaporation (inches)	
	Direction	Speed (mph)			Pan	Lake
Jan.	W	9.6	23.0	1.11		
Feb.	W	9.6	24.4	1.15		
Mar.	W	9.7	32.1	1.71		
Apr.	W	9.0	44.3	2.81		
May	S	7.8	54.4	2.72	5.8	4.1
June	S	7.4	65.3	2.61	6.3	4.4
July	W	7.0	70.4	2.91	7.4	5.3
Aug.	W	6.7	69.1	3.11	6.1	4.3
Sep.	W	7.2	61.8	2.61	4.2	3.0
Oct.	S	7.8	51.4	2.46	2.8	2.0
Nov.	W	9.6	39.9	2.26	5.8*	4.1*
Dec.	W	9.9	28.2	1.72		
Year	W	8.4	47.1	27.19	38.4	27.2

* Cumulative value November to April

TABLE 2. (CONT'D)

BASIN (CATCHMENT) DESCRIPTION

Name - Malvern

Location	Degrees	Minutes	Direction
Latitude	43	21	North
Longitude	79	46	West

Area - 57.6 acres 1974 Population 1,000 (est.)

Land Use - 100% Single Family Residential

Sewers - 100% Separate sewers

Soil types - Fox sandy loam, shallow phase, well-drained

Imperviousness - Total 34%

Directly connected 31%

Depression Storage pervious 0.18 in. (est.)

impervious 0.02 in. (est.)

Roughness pervious n = 0.25 (est.)

impervious n = 0.013 (est.)

Slope 0.01 ft/ft

Infiltration f_o = 3.0 in/hr f_{min} = 0.52 in/hr

α = .00115 sec^{-1} (decay rate in Horton's equation)

Street sweeping frequency - twice a year

Catch basin density - 1.21/acre (Total number - 70)

2.3 Land Use

The entire area is zoned as single family residential. Most of the houses were built in the early sixties, with virtually all development completed by 1964. There are no vacant lots or parks in the area; no construction activities were underway in the area during the data collection period.

There are 214 houses located within the catchment boundaries. The market price (1975) of the houses is within the range \$75,000 - \$100,000. All the properties are well-maintained. The average size of lots is estimated at about 9000 ft^2 (90 x 100 ft).

2.4 Catchment Surface Hydrology

For runoff calculations, two types of catchment surface are considered - pervious and impervious. In Malvern catchment, 37.5 acres are pervious and 20.1 acres are impervious.

The pervious area can be further subdivided into front yards (9.9 acres) and backyards (27.6 acres). The front yards drain directly onto road and their slope varies from 1 to 10%. The runoff from front yards may reach the sewer inlets in a relatively short time (10-25).

Backyards slope gently (2-3%) towards drainage swales running along the backline of lots and draining either onto streets, or into sewer inlets located in backyards. The runoff from backyards is thus retarded in comparison with that from front yards.

The time of concentration, defined here as the time required for the surface runoff from the remotest part of the drainage basin to reach the point under consideration (i.e. road gutters), was calculated for various slopes, and the results are shown in Table 3.

The calculation was made using the following empirical formula 2 :

$$t_c = 0.93 \frac{L^{0.6} n^{0.6}}{i^{0.4} s^{0.3}}$$

where: t_c is the overland flow time of concentration (minutes),

L is the length of overland flow (feet),

n is the Manning roughness coefficient,

TABLE 3. TIMES OF CONCENTRATION FOR FRONT YARDS AND BACKYARDS

a) Front yards

L = 35 ft; n = 0.25; i = 0.1 in/hr - 2.0 in/hr; s = 0.01 - 0.10

		Time of concentration (minutes)					
Slope		.01	.02	.03	.05	.08	.10
Rainfall Excess Intensities (in/hr)	0.1	34.0	27.6	24.5	21.0	18.2	17.0
	0.3	22.0	17.8	15.8	13.5	11.8	11.0
	0.5	17.9	14.5	12.9	11.1	9.6	8.9
	1.0	13.6	11.1	9.8	8.4	7.3	6.8
	2.0	10.3	8.4	7.4	6.4	5.5	5.2

Typical values correspond to slopes of 0.02 and 0.03

b) Backyards

L = 40 ft; n = 0.25; i = 0.1 in/hr - 2.0 in/hr; s = 0.01 - 0.03;

time of travel through swales 30-40 minutes.

		Overland time of Concentration (min)			Time of concentration (min)		
Slope		.01	.02	.03	.01	.02	.03
Rainfall excess intensities (in/hr)	0.1	36.8	29.9	26.5	76.8	69.9	66.5
	0.3	23.8	19.3	17.1	61.3	56.8	54.6
	0.5	19.4	15.7	14.0	54.4	50.7	49.0
	1.0	14.7	12.0	10.6	47.2	44.5	43.1
	2.0	11.2	9.1	8.0	41.2	39.1	38.0

Typical values are obtained for the slopes of 0.02 and 0.03.

i is the steady excess rainfall intensity (inches/hour),

s is the overland slope (feet/foot).

The infiltration has not been measured. The infiltration rates were calculated from Horton's formula 3 :

$$f(t) = f_i + (f_o - f_i)\, e^{-\alpha t}$$

where: $f(t)$ is the infiltration loss at time t (in/hr),

f_o is the infiltration loss at time t = 0 (in/hr),

f_i is the minimum infiltration loss (in/hr),

α (= .00115 sec^{-1}) is the decay coefficient,

t is time measured since the start of rainfall.

As the first approximation, the following values of the infiltration parameters were selected:

$f_o = 3.0$ $\qquad$ $f_i = 0.52$ $\qquad$ $\alpha = 0.00115$

Considering the type of soil on the catchment, a sandy loam, well-drained, the above values may be underestimating the actual infiltration losses.

Surface storage and roughness - both parameters were put equal to the SWMM default values, i.e. 0.184 inches and n = 0.25, respectively. Other estimates for these two parameters, as well as for the infiltration losses, will be obtained from runoff model calibrations.

The impervious area consists of roofs, roads, driveways and sidewalks.

All the roof leaders are connected to the storm sewers. The total roof area is 8.1 acres.

Roads - the total length of roads within the catchment is 1.87 miles, the total curb length is 2 x 1.87 = 3.74 miles and the road surface area is 6.68 acres. Most of the roads in the area serve for local access only. The only exception is Spruce Avenue (L = 0.26 miles) which serves also as a throughway running parallel to the major traffic routes.

Driveways - all the driveways (typically double driveways) in the area are paved and drain directly onto roads. The total surface area is 3.11 acres, the slope is 0.02 - 0.05.

Sidewalks - the paved sidewalks area is 1.63 acres. A certain portion of this area drains directly onto streets (or via driveways), and the rest drains onto narrow strips of grass between the sidewalk and road. The entire sidewalk area was considered to be directly connected to the sewer system.

The total imperviousness of the Malvern catchment was taken as $I = 19.5/57.6 = 34\%$.

Impervious surface storage was estimated from runoff simulations as 0.02 inches. Impervious surface roughness was taken as n = 0.013.

Basic information about the catchment surface is summarized in Table 4. The parameter values in Table 4 should be considered as first estimates only. Typically, these parameters, with the exception of the surface areas, are determined by a runoff model calibration. A further review of the values shown will be made after more field observations have been analyzed.

2.5 Sewer System

The Malvern catchment is served by a tree-type, converging separate sewer system (see Figure 2). All the sewers are made of standard concrete pipes. The sewer system is relatively new and in good condition. The pipe roughness was estimated as n = 0.013.

Pipe sizes, lengths, slopes, capacities, full bore velocities and times of travel are listed in Table 5.

The two most remote pipe inlets are those at the upstream ends of pipes 1 and 23. The times of travel for both inlets are shown below.

Pipe filled to	Approximate flow at the outfall	Time of Travel (minutes) Pipe 1	Pipe 23
.2D	3 cfs	17.3	18.1
.3D	7 cfs	13.6	14.3
.4D	13 cfs	11.7	12.3
.5D	20 cfs	10.4	10.9
1.0D	50 cfs	8.3	8.7

The total length of sewers is 9,135 ft; the total storage volume of the pipes (fully filled) is 18,650 ft^3.

TABLE 4. MALVERN CATCHMENT SURFACE CHARACTERISTICS

	Pervious Surface		Impervious Surface			
Area (acres)	38.09		19.51			
% of total (=57.6 ac)	66.0		34.0			
Ground Slope (ft/ft)	.01 - .03		.01 - .03			
Manning's n	.25		.013			
Surface Depression Storage (in)	.184		.02			
Infiltration rates - Maximum (in/hr)	3.0		-			
Minimum (in/hr)	0.52		-			
Decay rate (sec^{-1})	.00115		-			
Surface sub-type	Front yards	Back yards	Roofs	Roads	Drive-ways	Side-walks
Area (acres)	8.00	30.09	8.1	6.68	3.10	1.63
% of total (=57.6 ac)	14.0	52.0	14.0	11.6	5.4	3.0

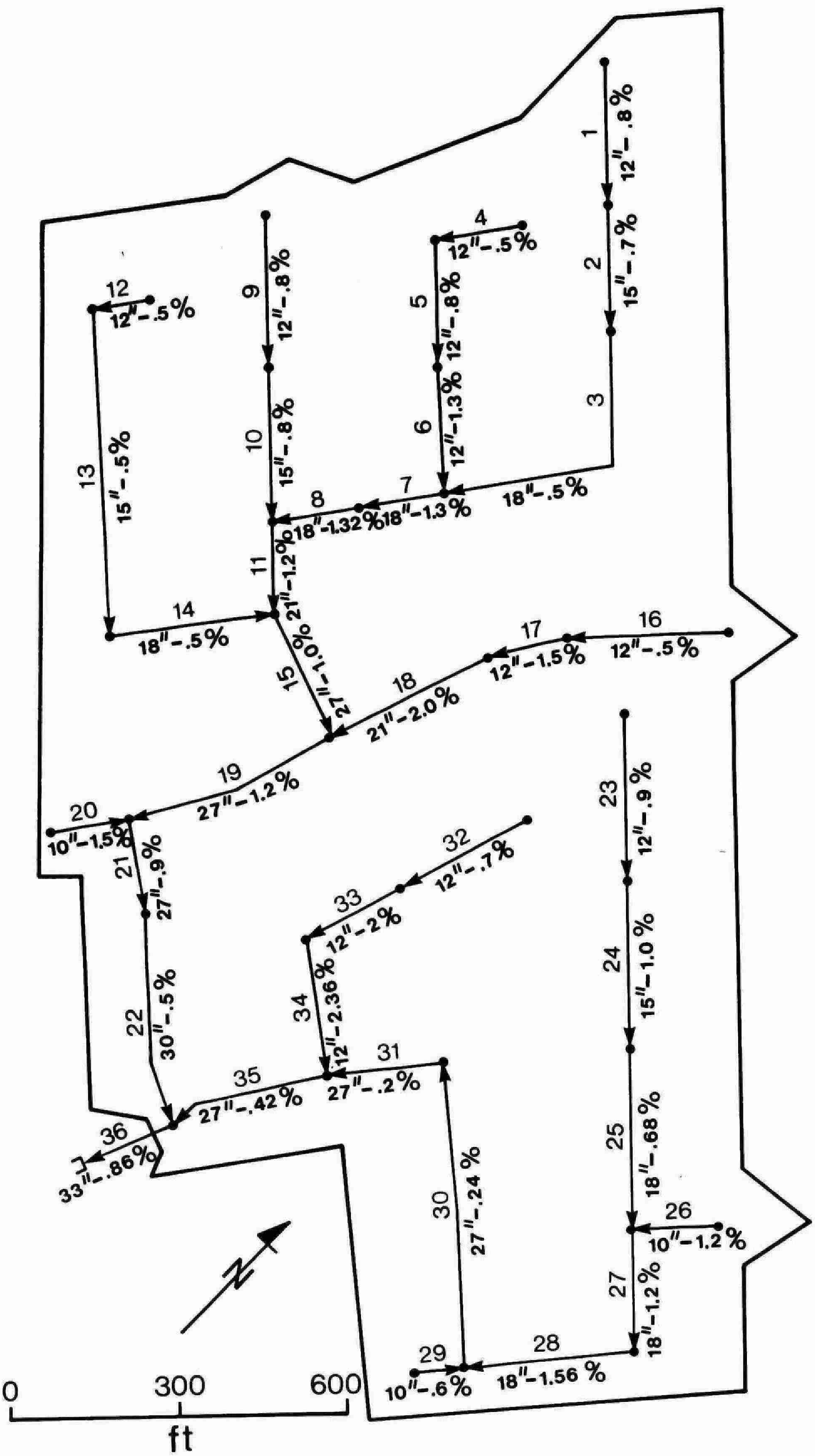

FIGURE 2. MALVERN CATCHMENT-STORM SEWER SYSTEM

TABLE 5. SEWER PIPES - BASIC DATA

Pipe number	Used in Simulations	Drains into pipe	Pipe diameter (in)	Invert slope (ft/ft)	Pipe length (ft)	Full Pipe capacity (cfs)	Full pipe vel. (fps)	Full Pipe time of travel (sec)
1		2	12	.008	295	3.2	4.1	70.0
2		3	15	.007	220	5.8	4.7	46.6
3	x	7	18	.005	525	7.4	4.2	124.7
4		5	12	.005	149	2.5	3.2	46.3
5		6	12	.008	210	3.2	4.1	51.6
6	x	7	12	.013	213	3.9	5.0	42.8
7	x	8	18	.010	151	10.5	6.0	25.2
8	x	11	18	.0132	148	12.5	7.0	21.0
9		10	12	.008	266	3.2	4.1	65.4
10	x	11	15	.008	260	5.8	4.7	55.1
11	x	21	21	.012	187	17.4	7.2	25.9
12		13	12	.005	132	2.5	3.2	41.0
13	x	14	15	.005	583	4.6	3.7	156.3
14	x	15	18	.005	298	7.4	4.2	70.8
15	x	19	27	.010	242	31.0	7.8	31.0
16		17	12	.005	229	2.5	3.2	71.1
17		18	12	.015	156	4.4	5.6	28.0
18	x	19	21	.020	304	22.5	9.3	32.5
19	x	21	27	.012	394	34.0	8.5	44.9
20		21	10	.015	140	1.6	2.8	49.3
21	x	22	27	.009	161	29.4	7.4	21.8
22	x	36	30	.005	390	29.1	5.9	65.9
23		24	12	.009	268	3.4	4.3	62.0
24		25	15	.010	300	10.5	6.0	50.3
25	x	27	18	.0068	301	8.7	4.9	61.3
26		27	10	.012	160	2.5	4.5	35.6
27	x	28	18	.012	224	11.5	6.5	34.3
28	x	30	18	.0156	292	13.2	7.4	39.2
29		30	10	.006	88	1.7	3.1	28.2
30	x	31	27	.0024	546	15.2	3.8	142.9
31	x	35	27	.002	194	13.9	3.5	55.6
32		33	12	.007	247	3.0	3.8	64.8
33		34	12	.020	172	5.1	6.4	26.7
34	x	35	12	.0236	238	5.5	7.0	34.0
35	x	36	27	.0042	280	20.1	5.1	55.3
36	x	outlet	33	.0086	176	49.2	8.3	21.3

3 CATCHMENT INSTRUMENTATION

The precipitation and runoff flows have been continuously monitored at a single point within the catchment boundaries (see Figure 1) and recorded on a single chart. The monitoring program was later expanded to include the quality of urban runoff, which has been monitored by collecting and analyzing discrete, sequential samples of storm water.

The instrumentation description presented in this section refers to the instrumentation installed in 1974. The less sophisticated instrumentation system used in the fall of 1973 is briefly described in Section 4.

3.1 Precipitation

The precipitation on the Malvern catchment is measured by one Leupold & Stevens tipping bucket raingauge of capacity of 0.01 inches. The raingauge output is recorded by the Leupold & Stevens Type A (Model 71) Recorder. The chart drive speed used, 2.4 inches/hour (61 mm/hour), makes it possible to discretize the records into one-minute intervals. Such a fine discretization was used for short, medium-to-high intensity storms. For long, low-intensity storms, a five minute discretization interval was used.

The location of the Malvern raingauge is shown in Figure 1. For some storms, the Malvern rain records were checked against those obtained from two municipal raingauges located within two miles of the Malvern catchment.

3.2 Runoff Flow Rate

Runoff flow rates are monitored continuously by means of a rectangular weir located at the outfall from the sewer system. Figure 3 shows basic dimensions of the installation.

A rectangular weir was selected because of its good accuracy for intermediate and large flows, and high flow capacities even for relatively small weir heads. Such high flow capacities helped to avoid the surcharging of the outfall pipe. The weir suffers from one shortcoming - low sensitivity for small flows (less than 3 cfs). This shortcoming is outweighed by the aforementioned advantages.

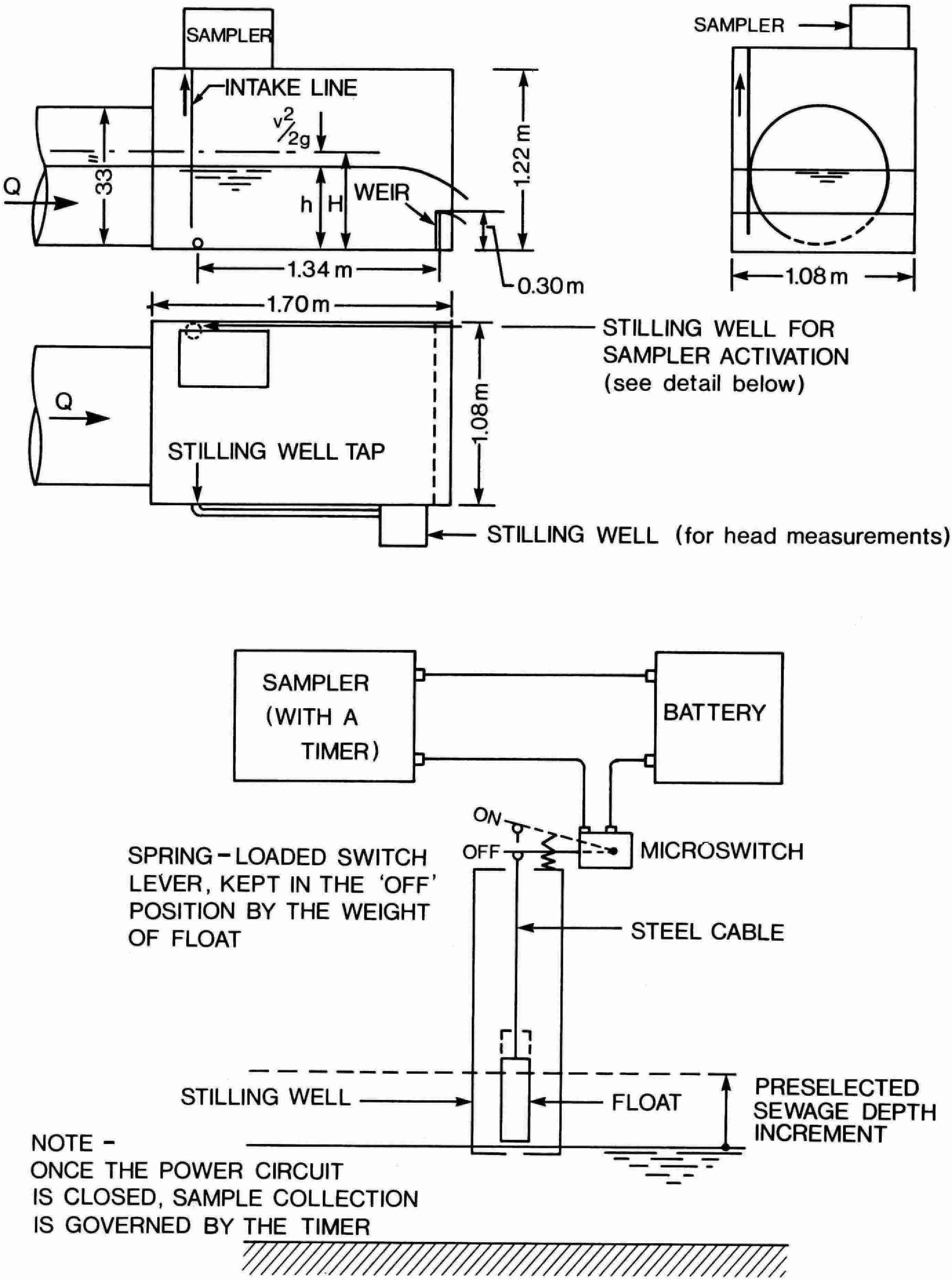

FIGURE 3. SAMPLER AND MEASURING WEIR INSTALLATION

Weir rating curve - The measuring weir (height = 1 ft, width = 3.53 ft) was calibrated in the Hydraulics Laboratory of the Canada Centre for Inland Waters. The weir box to be used in the field was attached to a steel pipe of the same diameter as the drainage outfall, and the weir was calibrated for flows ranging from 0.4 cfs to 16 cfs. The latter flow was the maximum attainable in the laboratory setup. Beyond the upper limit, the weir rating curve was extrapolated.

The results of calibration are plotted in Figure 4 together with a standard rectangular weir rating curve calculated from the following Kindsvater-Carter formula [4]:

$$Q = C_e \, L_e \, (H_e)^{3/2}$$

where:
- C_e = effective coefficient of discharge = 3.22 + 0.4 H/P,
- P = weir height (ft),
- H_e = effective head on weir crest (ft) = H + 0.003,
- H = weir head (ft),
- L_e = effective length of weir crest (ft) = L - 0.003,
- L = length of weir crest (ft).

The calibration data seem to deviate significantly from the standard weir curve. This deviation is systematic - the calibrated weir discharges all flows at smaller heads than those calculated from the aforementioned equation. This discrepancy is caused by the difference in the flow conditions upstream of the weir - the above formula was derived for a weir placed in a rectangular flume, whereas the calibration data were affected by a much higher approach velocity in the circular drain leading to the weir box. Under these circumstances, the extrapolated rating curve (i.e. for flow larger than 16 cfs) may not be reliable and, consequently, a scale model of the weir box was calibated for the entire flow range (0-80 cfs).

The final rating curve for the weir is shown in Figure 4.

Analysis of the rating curve indicated that the curve was defined with an accuracy better than $\pm$ 2% for flows larger than 3 cfs (i.e. at 95% level of confidence). For smaller flows, a lesser accuracy (2 - 8%) was achieved.

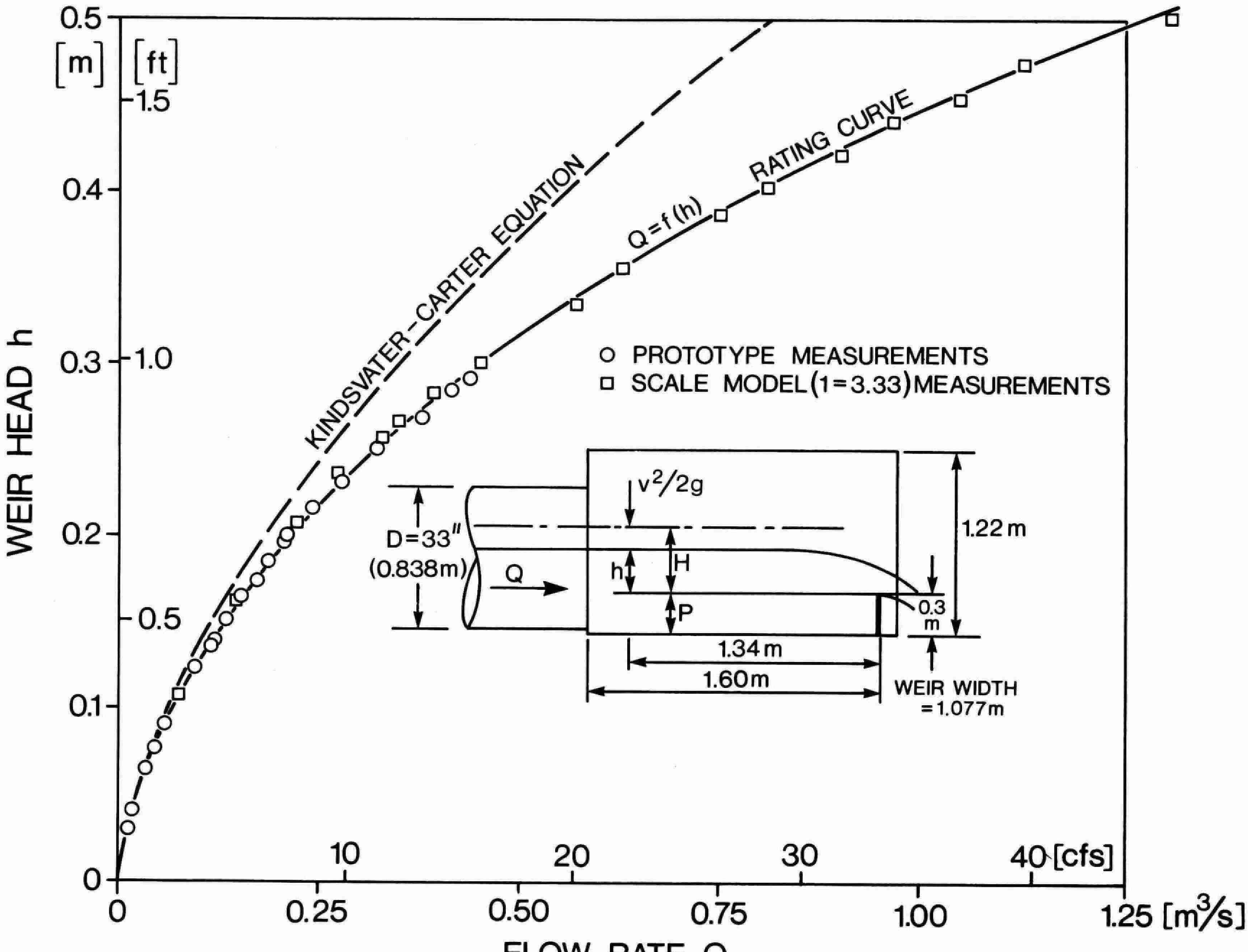

FIGURE 4. MEASURING WEIR - RATING CURVE

Weir head recording - The weir head is measured in a stilling well attached to the weir box and recorded by the Leupold & Stevens Water Level Recorder, Type A, Model 71. The standard recorder, which records the precipitation and water levels only, was modified to record also the operation of two automatic samplers. This arrangement offered a perfect time synchronization of all recorded data.

A metric version of the recorder was used with the ratio of the pen displacement to the water level displacement 1:5. The instrument accuracy was better than ± 3 mm (0.01 ft).

The recorder was driven by a synchronous motor; the drive speed was 57.6 inches per 24 hours (2.4 in/hr). The record resolutions were as follows:

time	-	1 minute
precipitation	-	0.01"
weir head	-	0.25 mm
sampler operation	-	1 minute

The instrument performed quite well; no malfunctions were encountered during the 2 1/2 years of operation.

3.3 Monitoring of Runoff Quality

The terms of reference of the study were expanded in the summer of 1974 for the runoff quality aspects. The runoff quality was to be monitored by means of collection of storm water samples, which were subsequently analyzed for a number of parameters. Initially, one automatic sampler was installed at the outlet (August, 1974). Frequent malfunctions of the sampler led to a considerable loss of data. In fact, the runoff quality was successfully monitored for less than 50% of all observed events. Consequently, a second sampler was installed in 1975 and both samplers were operated independently. As a result, about 80% of all events were successfully monitored. A description of the samplers and their operation follows.

Samplers

Two types of samplers were used in the study, the Sirco sampler B/ST-VS/24A-EX and a portable Sirco sampler MK-VS7. The main difference

between both samplers is the volume of samples - the former collects 1000 ccm samples and the latter 500 ccm samples. Both models are vacuum type samplers, battery operated. The sampling cycle consists of a presampling purge, sample withdrawal and postsampling purge. Up to 24 of sequential samples may be collected at a fairly high intake line velocity (about 1.0 m/s for lifts up to 2 m). The samplers can be controlled either by a timer, or by an external signal.

Sampler operation

Both samplers are activated automatically when the level of storm water in the outfall sewer rises by about 1.5 inches. A sketch of the activating mechanism is shown in Figure 3, a brief description follows. A two-inch plastic pipe fastened to the weir box functions as a stilling well for a small float, which is suspended on a string from the spring-loaded arm of a microswitch. For zero weir head, the weight of the float keeps the microswitch in the "off" position. When the water level and the float rise by about 1.5 inches, the load is taken off the microswitch, and the spring puts the switch arm into the "on" position. The microswitch then closes the sampler power supply circuit, and the time controlling the sample collection is activated. The first sample is withdrawn about one minute after the circuit closure; the remaining samples are collected at five-minute intervals. For some of the long duration storms, the sampling interval was changed to 15 or even 30 minutes to extend the total sampling period from two hours (i.e. 24 samples at five-minute intervals) to six or even 12 hours.

Sampler operation is terminated in two ways, either after 24 samples have been collected or when the stage in the weir box falls within 1.5 inches of the zero-flow level. The operation of both samplers have been recorded.

Processing of samples

Samples were removed from the samplers shortly after the end of runoff events and delivered to the Analytical Services Section of the Canada Centre for Inland Waters. There the samples were preserved and eventually analyzed. Whenever possible, the samples were analyzed for BOD, COD, Suspended Solids, Settleable Solids, Nitrates and Nitrites, and Phos-

phates. In some cases, additional tests were also performed. Quite frequently, the sample volume was not sufficient for all the above tests. In those cases, some tests had to be deleted. The details of these analyses and additional quality background information (e.g. quality of rainfall water, frequency of sweeping, cleaning of catchbasins) will be reported in subsequent volumes.

4. 1973 PRECIPITATION/RUNOFF DATA

4.1 Instrumentation

The data acquisition system used during the period Sept. 1, 1973 to Dec. 10 1973 differed from that described in the preceding section. A brief description follows.

Precipitation gauge - a standard AES tipping bucket and a 24-hour recorder were used. Bucket capacity was 0.01 inches. The recorder had a rather low chart speed - 0.59 inches per hour. The time resolution was about two minutes. The chart had to be changed every 24 hours.

Runoff flow rate - the weir arrangement described in Section 3 was used. The weir head was recorded by the Ott Vertical Water Level Recorder, Type R16. This is a very accurate water level recorder; the accuracy was about ± 0.005 ft. The chart speed is 0.63 inches per hour, time resolution about two minutes. The chart had to be changed every 24 hours.

The main drawbacks of this instrumentation were poor synchronization of precipitation/runoff records and the need to replace charts every day.

4.2 Precipitation/Runoff Data

The data collection period extended from September 1, 1973, to December 10, 1973. During this period, 20 minor-to-medium storm events were monitored. All these events are listed in Table 6.

Nine events were selected for further study, and for these events the ratios of measured runoff volume/measured precipitation volume were determined. With the exception of storm "G", the values of the above ratios were within the range 0.307-0.368. The average value (without storm "G") was 0.340, which is identical to the imperviousness of the catchment. This value 0.34 therefore indicates that virtually all the measured runoff originates on the impervious surface. Such a conclusion is plausible, since the recorded precipitation intensities were rather low, in most cases not exceeding the losses caused by infiltration and filling of surface depression storage on the pervious area.

Storm "G" (see Table 6) yielded an unusually large runoff. Nearly 50% of precipitation left the catchment as runoff, which would

TABLE 6. STORMS MONITORED FROM SEPTEMBER 1, 1973 TO DECEMBER 10, 1973

Storm	Date	Time	Duration (hrs)	Total Precipitation (in)	Total Precipitation (mm)	Selected for further study	Runoff / T. Precip.	Selected for simulation - sim. number
A	Sept. 17	1623-1958	3.6	.18	4.6			
B		2300-2416	1.3	.13	3.3			
C	Sept. 22	0656-0912	2.3	.84	21.3	X	.368	1
D		1117-1700	5.7	.18	4.6			
E	Sept. 23	0819-1148	3.5	.35	8.9	X	.337	2
F	Oct. 2	0130-0550	4.3	.12	3.0			
G		1930-2300	3.5	.77	19.6	X	.495	
H	Oct. 4	1552-2442	8.8	.27	6.9			
I	Oct. 13	1617-2355	7.6	.38	9.7	X	.307	3
J	Oct. 28-29	0418-0530	25.2	1.30	33.0	X	.358	4
K	Oct. 29-30	1145-1145	24.0	1.70	43.2	X	.356	5
L	Oct. 30-31	1125-2301	35.6	.30	7.6			
M	Oct 31-Nov. 2	2028-0910	12.7	.30	7.6			
N	Nov. 2	1452-1750	3.0	.19	4.8			
O	Nov. 14	0020-0940	9.3	.64	16.3	X	.352	6
P	Nov. 15	1138-1738	6,0	.77	19.6	X	.310	7
Q	Nov. 21	1200-2300	11.0	.29	7.4			
R	Nov. 29	0402-1525	11.4	.69	17.5	X	.328	8
S	Dec. 4-5	1235-0410	16.6	.33	8.4			
T	Dec. 9	1025-2115	10.8	.18	4.6			
			Σ = 206.2	Σ= 9.91	Σ = 251.9		Avg. = .340	

indicate large runoff contributions from the pervious area. A detailed examination of the precipitation record showed that the recorded precipitation was probably underestimated because of recorder malfunction caused by a low battery voltage. The storm "G" was therefore eliminated from further considerations.

The remaining eight events are characterized by relatively low average rainfall intensities - from 0.05 in/hr to 0.37 in/hr. The total precipitation per storm varied from 0.35 inches to 1.70 inches (Storm #5). The frequency of occurrence of these storms is now known, but it should be noted that on the Malvern catchment, only about 15 storms exceed annually the precipitation of 0.30 inches. The storm durations varied from 3.3 hours to 25.2 hours. The maximum rainfall intensity observed was 2.4 in/hour. None of the observed storms approached the severity of a design storm. Nevertheless, the observed storms represent typical events useful for the calibration of runoff models and for the studies of urban runoff quality. The details of the data collected appear in the Appendix.

5. RUNOFF SIMULATIONS WITH THE SWMM RUNOFF BLOCK

The selected precipitation-runoff events observed on the Malvern catchment were simulated with the Runoff Block of the SWMM. Such a procedure is acceptable, if according to the SWMM User's Manual [7] the following conditions are met:

- sewer pipes and gutters are the only hydraulic elements used in flow routing;
- no significant backwater effects occur; and
- the routing of quality constituents is unnecessary.

All these conditions were met in the case of the Malvern catchment.

Furthermore, the Runoff Block could be run on an in-house computer (CDC 3300), whereas the inclusion of the Transport Block in the simulations would require the use of a larger, commercial computer facility. Comparative runs with the Runoff Block routing and Transport Block routing will be made in the subsequent stages on the study.

At this stage of the study, the simulations were made with a partially calibrated SWMM. The parameters which could not be determined directly were assumed to be equal to the default values built into the SWMM. The only exception was the surface storage on the impervious area. The value of 0.02 inches rather than 0.062 inches (i.e. the default value) was used.

5.1 Catchment Discretization

For modelling purposes, the catchments are subdivided into a number of subcatchments representing the physical drainage system. There is no exact procedure for catchment discretization, and the number of elements depends on the modeller's choice. The agreement between the observed and simulated runoff events seems to be the only way to evaluate the correctness of the discretization selected, provided that the model is fully applicable to the catchment studied and model parameters were correctly selected.

Drainage patterns on the Malvern catchment are shown in Figure 5. Following these patterns and sewer layout, the catchment was subdivided into 10 subcatchments. The sewer system was represented by 21 pipes (see Figure 5). The characteristics of subcatchments are given in Table 7. As

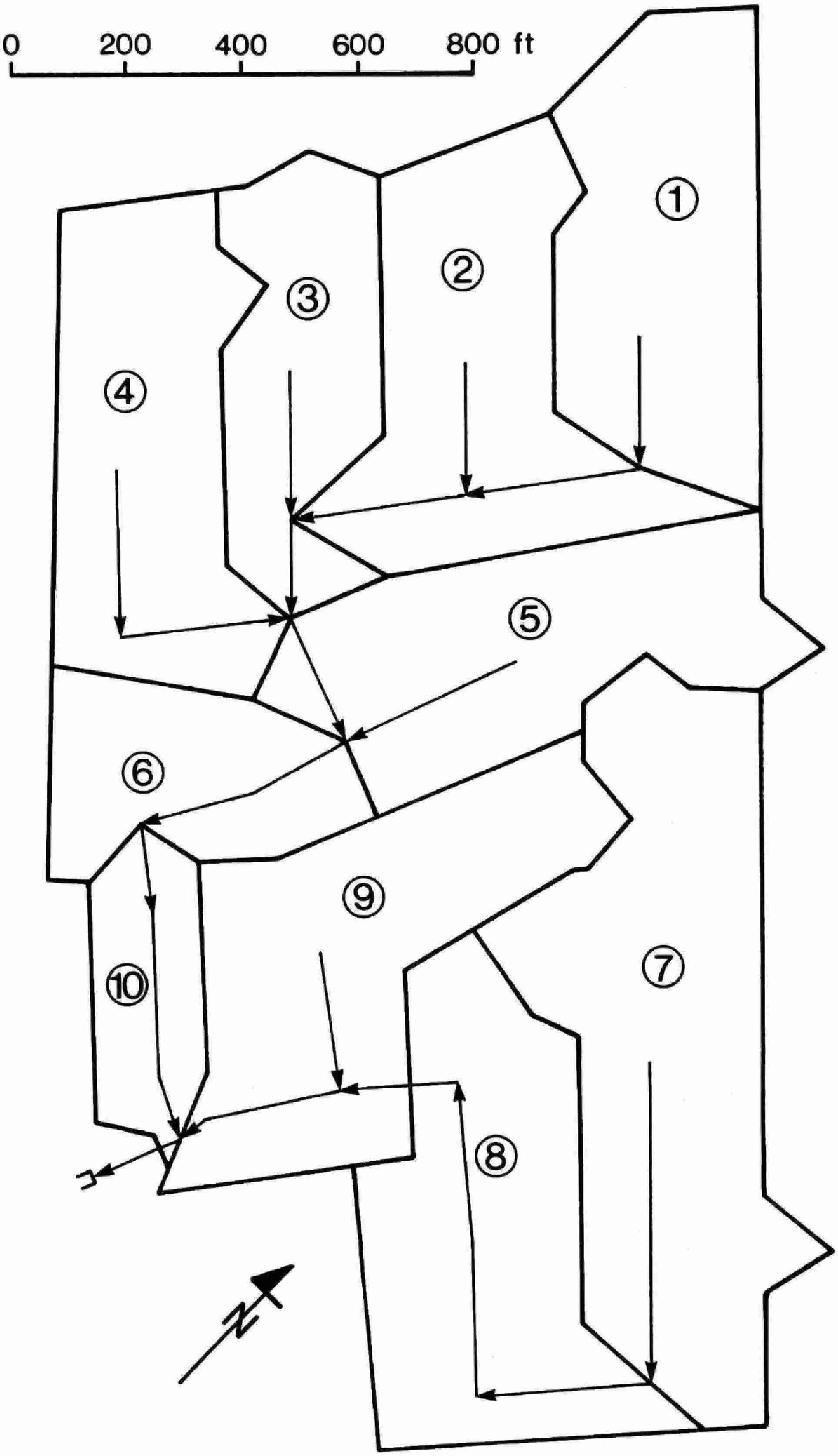

FIGURE 5. MALVERN CATCHMENT DISCRETIZATION

TABLE 7. SUBCATCHMENT CHARACTERISTICS

Subcatchment Number	1	2	3	4	5	6	7	8	9	10
Sewer pipe for drainage	3	6	10	13	18	21	25	30	34	22
Area (acres)	5.64	6.23	3.87	6.01	6.12	2.26	9.47	6.62	8.14	2.14
Impervious area (acres)	1.89	2.21	1.66	2.81	1.89	1.22	2.74	2.11	1.87	1.07
Pervious area (acres)	3.75	4.02	2.21	3.20	4.23	2.14	6.73	4.51	6.27	1.07
Imperviousness (%)	33.8	35.7	42.5	46.8	31.0	36.0	28.8	32.0	23.1	50.9
Catchment SWMM width (ft)	1400	2400	1390	1930	1930	1060	2550	2050	2180	1100
Length of curb (100 ft)	17.48	23.18	15.42	22.07	20.33	11.25	30.47	21.75	24.76	10.77
Number of catch basins	8	4	7	7	7	5	11	7	8	4

discussed later, the selected catchment discretization was found suitable and good simulation results were obtained. If desirable, the 10 subcatchments could be aggregated into a smaller number of catchments to save on computer costs. This would require, however, considerable changes in the simulated sewer system, and such changes, rather remote from the physical reality, were considered inappropriate here. The resulting savings on computer costs would be negligible in the case of the Malvern Catchment.

Only 21 sewer pipes out of the total number of 36 pipes were used in the model simulations. The neglect of 15 pipes results in the reduction of the total pipe storage volume by 13% only, since only small pipes were neglected. This loss of storage was then partially compensated by increasing the diameters of some pipes, typically, along the route from the subcatchment inlet to the downstream subcatchment boundary. This was done to avoid possible sewer surcharging which may occur in model simulations, but would not occur in real life. Such a surcharging would be caused by the assumption in the runoff simulations that all the surface runoff flow enters the sewer system through a single inlet located close to the centroid of the subcatchment area. At this point, the sewer pipe is not designed to carry the total flow, since in the real sewer system the runoff flow enters the sewers through a number of inlets, and only the very downstream sewer pipe has a capacity sufficient to carry the total flow.

After increasing the sewer capacities as outlined above, the actual loss in the pipe storage became negligible.

5.2 Simulation Results

For the eight storms selected, the runoff simulations were performed with the Runoff Block of the SWMM. In the first three events, the time step and the precipitation interval were two minutes. For the remaining five events, the time step was five minutes and the precipitation interval varied from five to ten minutes. The longer precipitation intervals were found adequate for the long-duration, low-intensity storms. The use of a time step shorter than the precipitation interval was necessary in order to achieve the numerical stability of the flow routing scheme.

The values of model parameters used in the simulations are shown in Table 4. With the exception of the surface depression storage on

impervious areas, these values are identical to the default values built into the SWMM.

No significant surcharging has occurred for the eight storms studied. Some minor surcharging occurring in the upstream parts of the sewer network was simulated by the model by storing the flows in excess of pipe capacities at the sewer junctions and releasing the volume stored back into the sewer system later, when the flow fell below the pipe capacity. The volumes stored in this way have not exceeded 200 ft^3 and are negligible in comparison with the total runoff volumes.

The results of simulations are summarized in Table 8 and presented pictorially in Figures 6-9. Table 8 contains information on total volumes of measured precipitation, measured runoff, simulated runoff, simulated surface depression storage (on pervious areas) and infiltration. Runoff peak flows and times to peak are also included for both observations and simulations.

In Figures 6-9, observed and simulated runoff hydrographs are plotted. The plots of the simulated hydrographs were shifted along the time axis to achieve the best visual agreement between the measured and simulated hydrographs. The magnitude of these shifts is indicated in the figures.

5.3 Discussion of Results

The results presented here have two major limitations: a) the small number of observations, and b) in none of these events did the pervious areas contribute significantly to the total runoff. Both these shortcomings are likely to be corrected in later stages of the project as more field data becomes available.

5.3.1 Runoff volumes

The total runoff volumes were simulated by the Runoff Block fairly accurately. The average value of the ratio of measured to simulated runoff volumes is 1.03 (see Table 8). The standard deviation about mean is 0.06. Both these values represent a statistically significant improvement over the SWMM results presented previously by Heeps and Mein [1], and Marsalek et al [5]. This can be explained by the accuracy of the Malvern data, which were checked more rigorously than the data from the previous studies.

The observed rainfall intensities rarely exceeded the infiltration capacity considered in the model and, therefore, only runoff from the imper-

TABLE 8. SUMMARY OF RUNOFF SIMULATIONS WITH THE RUNOFF BLOCK OF THE SWMM ON THE MALVERN CATCHMENT

Storm Number	1	2	3	4	5	6	7	8	Average	Standard deviation (% of aver)
Precipitation (in)	.71	.36	.31	1.15	1.48	.60	.71	.48		
Precipitation volume ($x10^3$ ft^3)	148.5	75.3	64.8	240.5	309.5	125.5	148.5	100.4		
Measured runoff volume ($x10^3 ft^3$)	54.6	25.4	19.9	86.1	110.3	44.2	46.1	32.8		
Runoff volume/Precipitation volume	.368	.337	.307	.358	.356	.352	.310	.328	.340	7%
Volume of simulated gutter flow ($x10^3 ft^3$)	49.5	24.4	20.9	80.2	103.7	41.4	49.2	32.8		
Volume of simulated infiltration ($x10^3 ft^3$)	98.2	49.8	42.9	159.2	204.6	83.0	98.2	66.4		
Surface depression storage volume ($x10^3 ft^3$)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1		
Simulated runoff volume/precipitation volume	.333	.324	.323	.333	.335	.330	.331	.327	.330	1.3%
Measured runoff volume/simulated runoff volume	1.10	1.04	0.95	1.07	1.06	1.06	.94	1.00	1.03	6%
Measured runoff peak flow (cfs)	32.4	25.2	8.1	8.5	10.8	10.4	6.4	9.8		

TABLE 8. (CONT'D)

Storm Number	1	2	3	4	5	6	7	8	Average	Standard deviation (% of Aver.)
Simulated runoff peak flow (cfs)	34.5	22.4	8.3	6.0	8.8	9.4	6.9	9.6		
Measured peak/ simulated peak	.94	1.13	.98	1.42	1.23	1.11	.93	1.02	1.095	15%
Measured time to peak (minutes)	39	113	96	385	455	375	132	228		
Simulated time to peak (minutes)	37	118	94	390	430	385	138	244		
Measured time to peak/simulated time	1.05	.96	1.02	.99	1.06	.97	.96	.93	.99	4.7%

vious areas was simulated. Consequently, the simulated runoff volume is a nearly constant proportion of the total precipitation volume, as seen in Table 8.

The variation in the ratio of simulated to measured runoff volumes closely follows that of the ratio of the measured runoff volume to the measured precipitation volume. A further analysis of the latter ratio indicated that there was a positive correlation between the total precipitation and the ratio of runoff to precipitation volumes. In other words, the larger the total precipitation, the larger percentage of precipitation is transformed into surface runoff. Such a finding is in agreement with the expected behaviour of the catchment.

By model calibration, the average value of the ratio of measured to simulated runoff volumes could be made equal to one by increasing the imperviousness of the catchment, reducing the infiltration and reducing the surface storage on both pervious and impervious areas. As elaborated below, no physically based justification was found for any of these adjustments.

An increase in the catchment imperviousness could be explained by a possible error in the determination of the imperviousness from a map and from an air photo. The imperviousness used in the simulations (34%), however, may be already on the higher side of estimation, since all of the sidewalk area (3% of the total area) was included in the directly connected impervious area, though some loss of runoff from the sidewalks may occur. A further increase in the catchment imperviousness is therefore unwarranted at present.

The impervious surface storage of 0.02 inches appears to be a minimum value which cannot be further reduced. An identical value was adopted in a previous calibration of the SWMM [6].

The selected infiltration rates do not appear to be excessive for the sandy, well-drained soil occurring on the Malvern catchment (see Table 2). The evaluation of these rates will be possible only after some runoff data for very intense, long duration storms have been collected, and some infiltration measurements have been made. At the same time, the surface storage on the pervious areas will be evaluated.

The small underestimation of the simulated runoff volumes may be caused by an undercatch of the Malvern precipitation gauge. A further study of this question will require the installation of a second raingauge on the

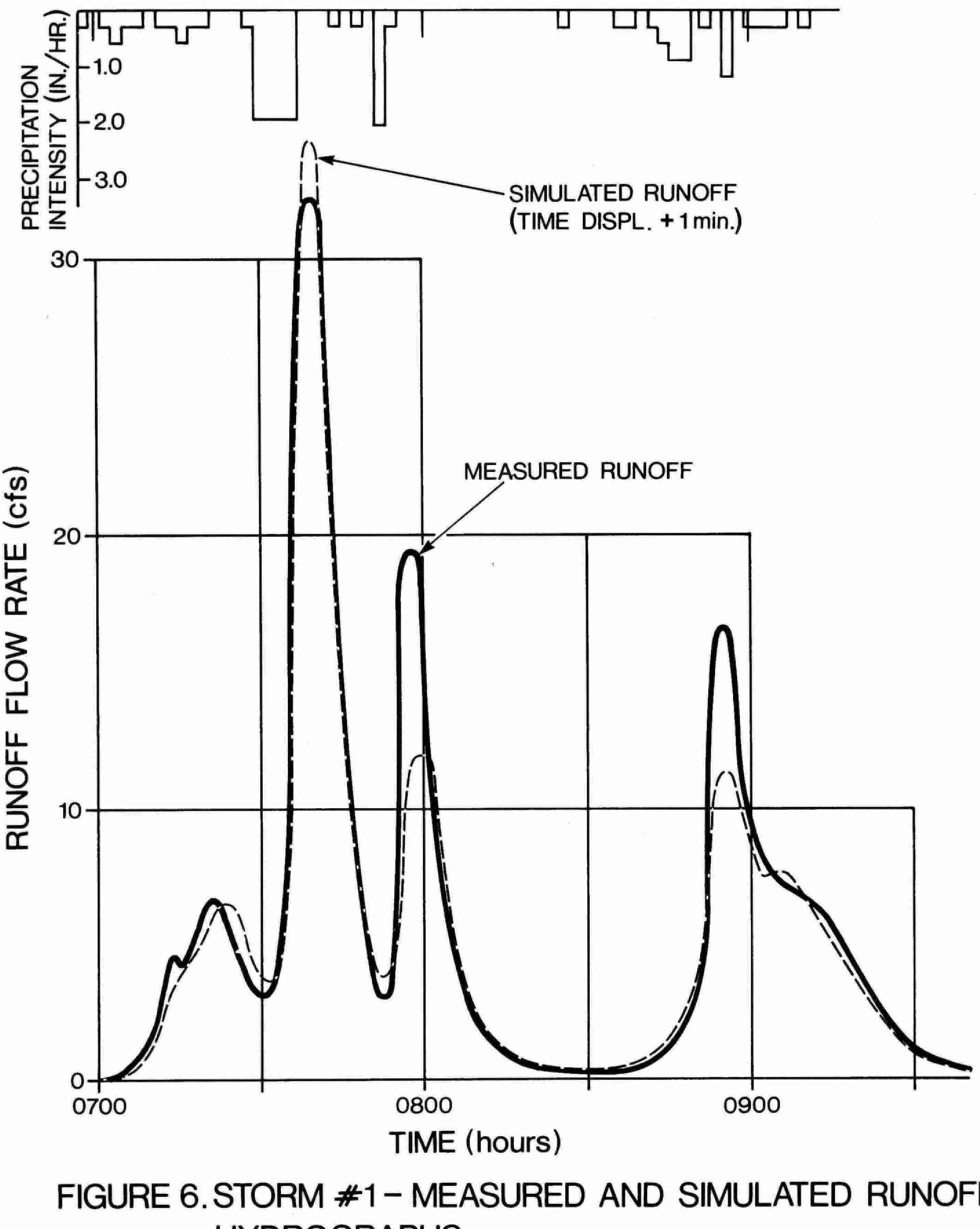

FIGURE 6. STORM #1 – MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

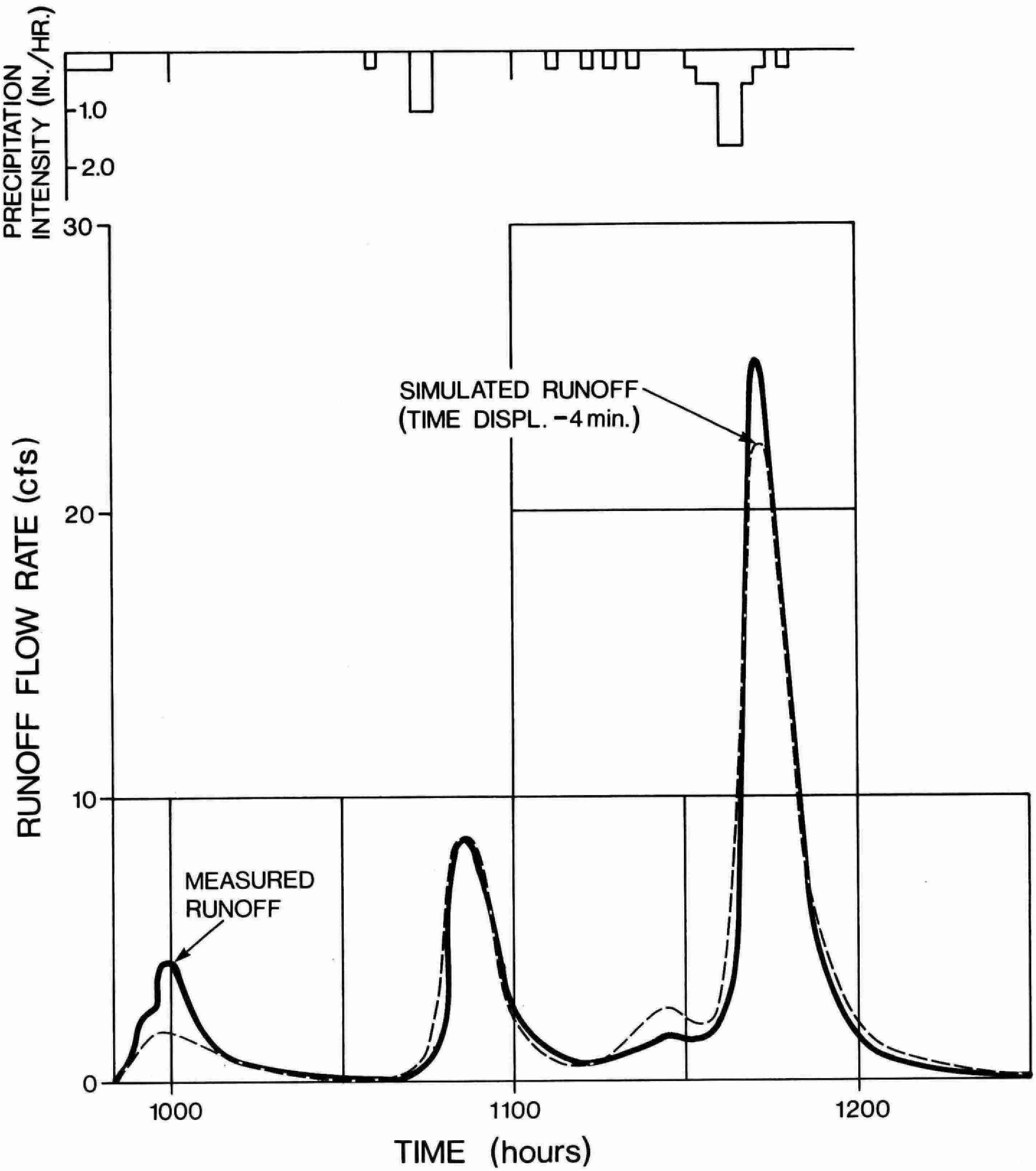

FIGURE 7. STORM #2-MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

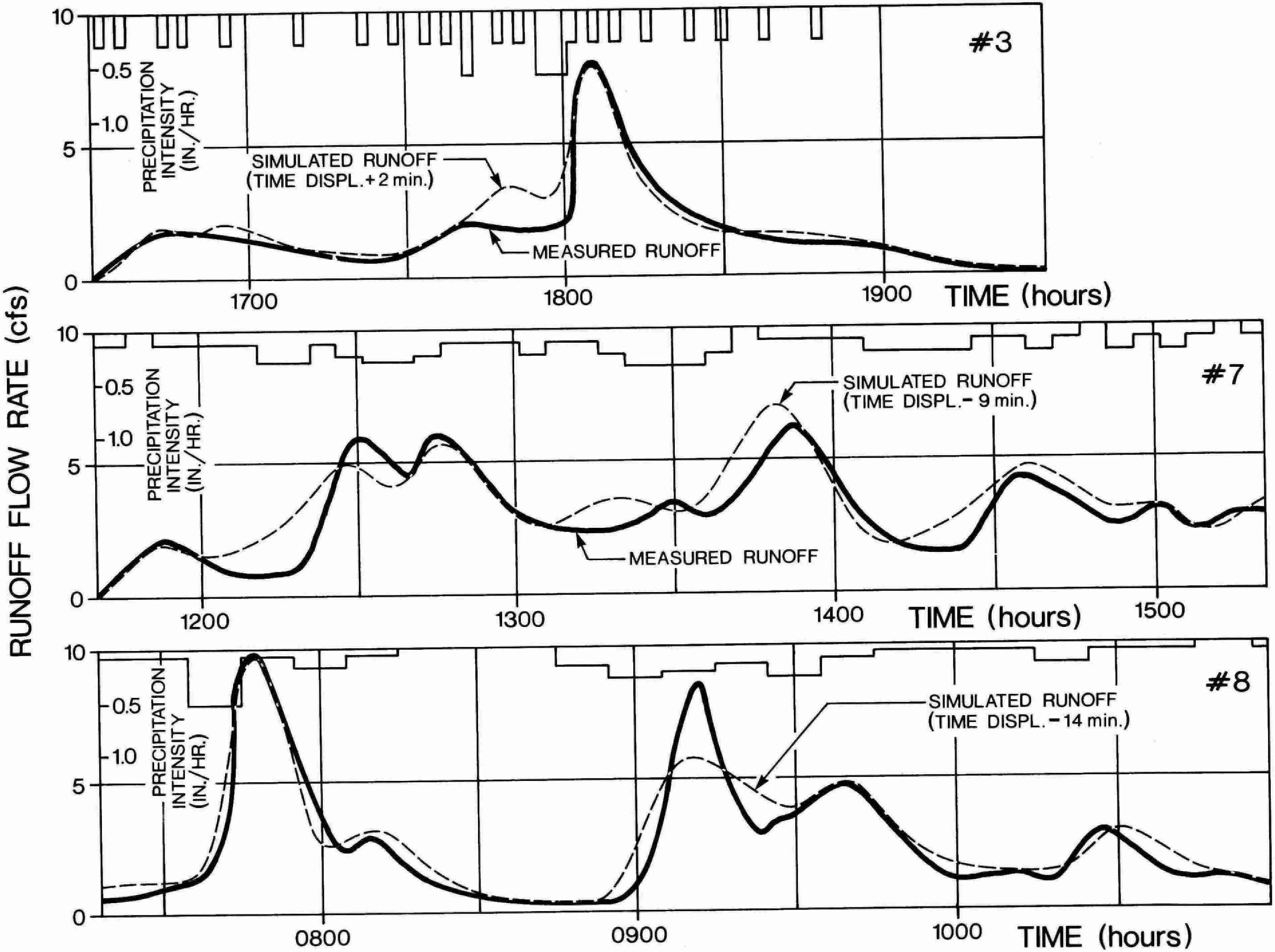

FIGURE 8. STORMS #3, 7, 8 – MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

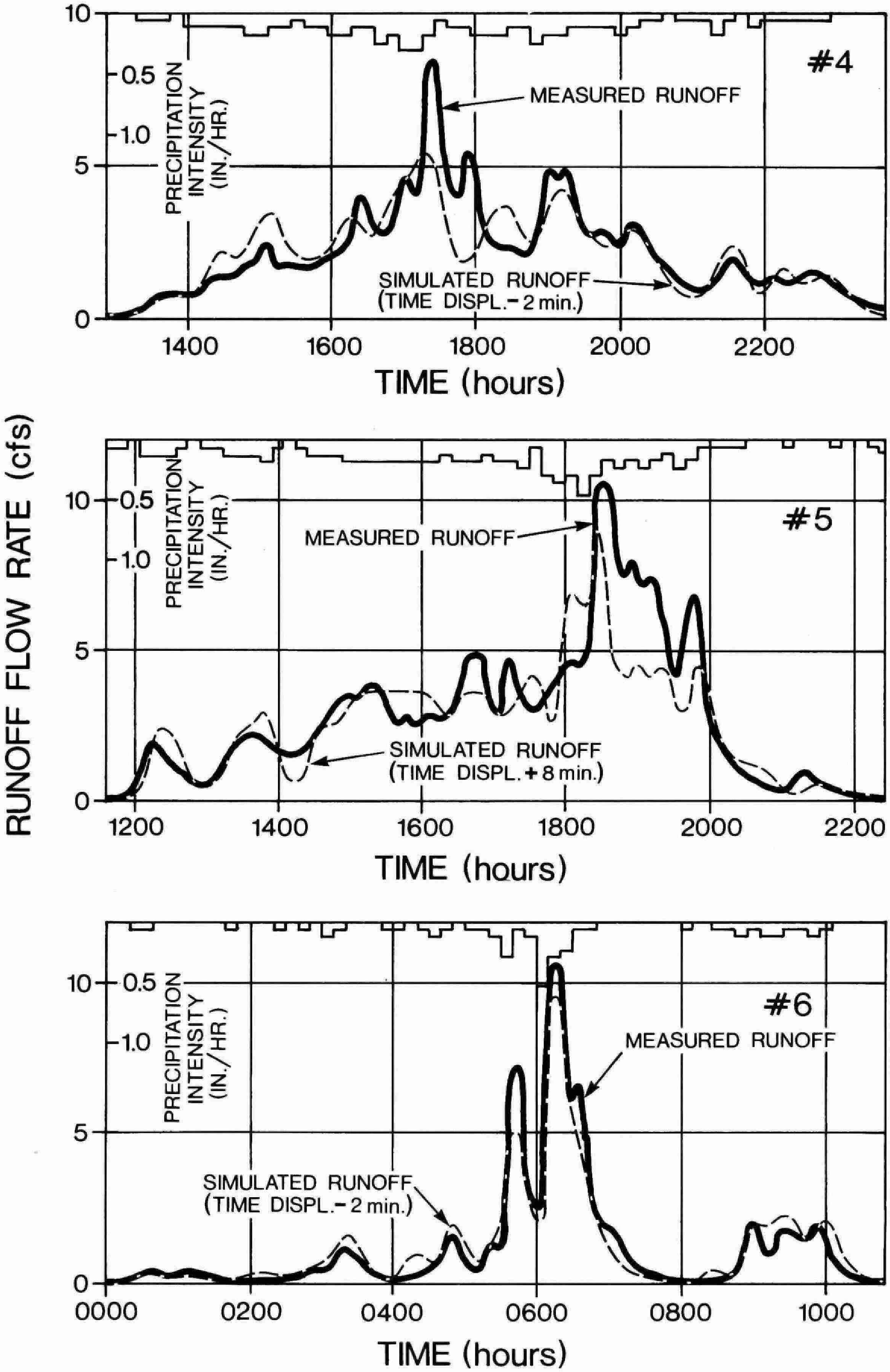

FIGURE 9. STORMS #4,5,6-MEASURED AND SIMULATED RUNOFF HYDROGRAPHS

Malvern catchment within say 0.5 miles of the first gauge. Both municipal raingauges are too remote (2.3 miles) for this purpose.

In any event, the small underestimate in the simulated runoff volumes of the order of 3% is fully acceptable from the practical point of view.

5.3.2 Runoff peak flow rates

Measured and simulated runoff peak flow rates are shown in Table 8. In most cases, the runoff peaks were somewhat underestimated, which is consistent with the underestimation of runoff volumes. The variance of results about the mean was about 15%, not significantly different from the previous study [5]. The simulations of peaks seem to be fairly accurate, particularly for simulations done for short time interval precipitation data and short simulation time steps (see storms #1, 2, and 3). Larger deviations encountered for long duration, low intensity storms (4-8) are partly caused by the rainfall discretization into 10 minute intervals. Short interval, high intensity rainfall tends to cause higher runoff peaks than the same volume of precipitation spread over a longer time interval.

The largest deviation of the simulated peaks from the measured ones was found in the case of storm #1 for the third and fourth peaks (see Figure 6). Otherwise in this storm, the first two peaks were simulated quite accurately and also the agreement between the entire measured and simulated hydrographs was perfect. It is felt, therefore, that the underestimation of the simulated third and fourth peaks was caused by the underestimation of rainfall intensity rather than by a biased model structure, which would have affected the simulation for an extended period, if not for the entire storm.

In general, the simulation of runoff peaks was found satisfactory for practical purposes. More storms of higher intensity will be needed to draw conclusions about the predictability of Malvern runoff peaks with the SWMM model.

5.3.3 Time to peak

The observed and simulated times to peak are summarized in Table 8. A fairly good agreement between the both sets of values was found. In fact, when describing the goodness of fit of the simulated times to peak to the observed ones by the ratio of simulated to observed values, the average

value of this ratio was 0.99 and the standard deviation was 4.7%. These results are better than those reported previously [5, 6].

The difference between the simulated and observed times is described by the time shifts indicated in Figures 6-9. The magnitude of these shifts varies from -14 to 8 minutes. Much of this variation is likely to be caused by the error in the synchronization of the flow and precipitation records, and possibly by the location of the raingauge in the southwest corner of the catchment. A possible effect of the raingauge location was checked. For the storms approaching from the southwest, south, and southeast directions, the simulated hydrographs should precede the observed ones. For the north, northeast, east, and northwest directions, the simulated hydrographs should follow the observed ones. For the west direction, both hydrographs should be synchronized. Note that these errors in the timing of the simulated hydrographs are bound to be small, of the order of one to three minutes, and for the 1973 data are of the secondary importance in comparison with the synchronization error in the precipitation and flow records.

The effect of the storm movement on the simulated hydrographs should be most pronounced for the northwest-southeast direction, i.e. along the longitudinal axis of the catchment, and the least pronounced for the southwest-northeast direction. Only 17% of all the observed storms moved in the former direction, and 45% of the storms moved in the latter direction.

In summary, the timing of the simulated hydrographs appears to be fairly good. A further analysis of the effects of the raingauge location and the movement of storms on the timing of simulations should be possible with the well-synchronized records collected on the Malvern catchment since 1974.

ACKNOWLEDGEMENTS

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W. Ellis of the Hydraulics Research Division, Canada Centre for Inland Waters, provided invaluable technical assistance throughout the project.

REFERENCES

1. Heeps, D.P., and Mein, R.G. "An Independent Evaluation of Three Urban Runoff Models", Civil Engineering Research Report No. 4, Monash University, Victoria, Australia, 1973.

2. Henderson, F.M., and Wooding, R.A. "Overland Flow and Groundwater Flow from a Steady Rainfall of Finite Duration", Journal of Geophysical Research, Vol. 69, No. 8, April 1964, pp. 1531-1540.

3. Horton, R.E., "An Approach Toward a Physical Interpretation of Infiltration Capacity", Soil Science Society Proceedings, Vol. 5, 1940.

4. Kindsvater, C.E., and Carter, R.W., "Discharge Characteristics of Rectangular Thin-Plate Weirs", Transactions, ASCE, Vol. 124, 1959, p. 772.

5. Marsalek, J., Dick, T.M., Wisner, P.E., and Clarke, W.G., "Comparative Evaluation of Three Urban Runoff Models", Water Resources Bulletin, Vol. 11, No. 2, pp. 306-328, April 1975.

6. "Review of Canadian Design Practice and Comparison of Urban Hydrologic Models", Research Report No. 26, Canada-Ontario Agreement Research Program, October 1975. (Available from: Training and Technology Transfer Division, Environment Canada, Ottawa, Ontario, K1A 0C8).

7. "Storm Water Management Model", Volumes I-IV, Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series, 11024 DOC 09/71, Washington, D.C., Sept. 1971.

A P P E N D I X

PRECIPITATION AND RUNOFF DATA COLLECTED ON THE MALVERN URBAN TEST CATCHMENT FROM SEPTEMBER 22, 1973 to NOVEMBER 28, 1973

Storm No.1 - Sept. 22, 1973

Time-hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
0656	start		
58	1		
0700			
02	1	.13	.004
04	2		
06	1		
08	1		
10			
12	1	4.24	.120
14	1	3.99	.113
16	2		
18	1		
20	1		
22		5.87	.167
24		5.87	.167
26			
28	1	2.85	.081
30	6.5		
32	6.5	4.24	.120
34	6.5		
36	6.5	31.06	.882
37		31.82	.904
38			
39		31.82	.904
40			
42		31.06	.882
44	1		
46		4.75	.135
48	1		
0750			
52	7	2.85	.081
53		3.29	.093
54	1	3.75	.106
56		19.28	.548
58		19.28	.548
0800		.55	.016
02			
04		4.75	.135
06			
08		2.44	.069
10			
12			
14			

Time-hours and minutes	Raingauge tips (0.1" each	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
0815		.82	.023
16			
18			
19		.47	.013
20			
22			
24			
26			
28	1		
29		.20	.006
30			
32			
34			
36			
37		.20	.006
38	1		
40	1		
42		.37	.011
44	1		
46	2		
48	3		
50	3	2.44	.069
52			
54	1	16.10	.457
55		16.10	.457
56			
58	4		
0900			
01		7.76	.220
02	1		
04	1		
06	1		
08	1		
10			
12	1		
14	end		
15		5.87	.167
0924		2.06	.059
0932		.82	.023
0935		.58	.016
0938		.37	.011
0948		.20	.006
1005		.07	.002
1035		.02	.001

Storm No.2 - Sept. 23,1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
0946	start		
48	1		
49		.03	.001
50	1		
52	1		
53		.90	.026
54	1		
55		2.40	.068
56			
57		2.48	.070
58			
59		4.29	.122
1000			
02			
03		2.17	.062
04			
06			
08		.84	.024
10			
12			
14			
15		.43	.012
16			
18			
20		.26	.007
22			
24			
25		.20	.006
26			
28			
30		.13	.004
32			
34			
36			
38			
40	1		
42		.09	.003
44			
46		.90	.026
48	3.5		
50	3.5		
51		8.59	.244
52			
54			

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1056			
58			
1100		2.36	.067
02			
04		1.17	.033
06			
08		.68	.019
10			
12	1	.60	.017
14			
16			
18	1		
20		.90	.026
22	1		
24			
26	1		
28		1.64	.047
30			
32			
33		1.48	.042
34			
36	1		
37		2.56	.073
38	2		
40	2	11.78	.335
42	5.5		
43		25.26	.717
44	5.5		
46	2		
48	1		
50	0		
51		6.66	.189
52	1		
54	end		
1158		2.17	.062
1201		1.17	.033
1207		.68	.019
1210		.54	.015
1215		.43	.012
1300		.09	.003
1320		.01	.000

Storm No. 3 - Oct.13, 1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1614	start		
16	1		
18			
20			
22	1		
24			
26	1		
28			
30		.00	.000
32	1		
34		.95	.027
36	1		
38			
40			
42		1.88	.053
44	1		
46			
48	1		
50		1.88	.053
52			
54			
56	1		
58			
1700		1.54	.044
02			
4			
06			
08			
10	1		
12			
14			
16			
18			
20		.70	.020
22	1		
24			
26		.70	.020
28	1		
30			
32			
34	1		
36			
1738	1		
40		2.25	.064
42	2		
43		2.25	.064
44			
46			
48	1		
50			
52	1		
54			
56	2		
58	2		
1800	2	2.06	.059
02	1	5.02	.143
04			
06	1	8.45	.240
08			
10	1	6.47	.184
12			
14		3.99	.113
16	1		
18			
20			
22			
24	1		
26			
28			
30	1	1.88	.053
32			
34			
36			
38	1		
40		1.54	.044
42			
44			
46			
48	1		
50	end	1.54	.044
1920		.28	.008
35		.20	.006

Storm No.4 - Oct.28-29, 1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1210	start		
20	1		
30	1		
40			
50			
1300			
09		.11	.003
10			
18		.20	.006
20			
30	1	.58	.016
40	1	.75	.021
50	1	.70	.020
1400		.65	.018
10	1.8		
20	1.8		
22		1.36	.039
30	1.8		
31		1.43	.041
38		1.43	.041
40	1.8		
45		1.71	.049
50	1.8		
57		1.88	.053
1500	3		
03		2.44	.069
10	3	1.64	.047
20	2		
23		1.74	.049
30	2		
40	1	1.68	.048
49		2.10	.060
50	2		
1600	2		
01		1.99	.057
10	3	2.18	.062
20	3		
23		3.94	.112
30	2		
40	2		
42		2.64	.075
50	4		
56		3.47	.099

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1700	3		
03		4.65	.132
10	4	3.89	.110
20	5		
26		8.52	.242
30	3		
36		4.49	.128
40	1		
44		3.89	.110
50	2		
54		5.46	.155
1800	2		
08		2.60	.074
10	3		
20	3		
25		2.44	.069
30	3		
31		2.25	.064
40	2		
46		2.06	.059
50	2		
1900	4		
02		4.75	.135
08		4.49	.128
10	3		
13		4.75	.135
20	3		
23		3.47	.099
30	2		
33		2.60	.074
40	2		
44		2.77	.079
50	2		
54		2.21	.063
2000	2		
04		3.02	.086
10	3		
14		2.98	.085
20	2		
24		1.95	.055
30	1		
35		1.81	.051
40	1		

Storm No.4 - Continuation

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
2046		1.09	.031
50			
2 100	1		
03		.84	.024
10	1		
18		1.36	.039
20	1		
27		1.88	.053
30	3		
40	1		
48		1.18	.034
50			
59		1.39	.039
2200	2		
10	1		
18		1.12	.032
20	1		
30	1	1.42	.040
40	1		
44		1.39	.039
50	1		
58		.95	.027
2300	1		
05		.84	.024
10	end		
2330		.37	.011
0318		.01	.000

Storm No. 5 - Oct.29-30, 1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1120	start		
30	1		
40	1		
50			
52		.01	.000
1200	2		
10	2		
17		2.06	.059
20	2		
30	1		
40			
50	1		
1300	1	.41	.012
10	2		
20	2		
27		1.85	.053
30	2		
40	3	2.10	.060
50	1		
1400			
07		1.43	.041
10	1		
20	2		
30	2		
40	2		
45		2.56	.073
50	3		
55		3.43	.097
1500	3		
06		3.29	.093
10	3		
18		4.04	.115
20	3		
30	3	3.41	.097
40	3	2.59	.074
45		2.69	.076
50	3		
56		2.52	.072
1600	3		
07		2.85	.081
10	2		
18		2.64	.075
20	3		
30	3		

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1638		4.80	.136
40	3		
43		4.75	.135
50	3	4.85	.138
58		3.20	.091
1700	2		
1705		2.80	.080
10	3		
15		4.75	.135
20	3		
25		3.37	.096
30	4		
37		2.96	.084
40	1		
50	5		
52		3.67	.104
1800	6		
05		4.59	.128
10	5		
15		4.29	.122
20	8		
21		4.84	.137
29		9.61	.273
30	5		
37		10.86	.308
40	3		
45		9.68	.275
50	4		
54		7.37	.209
59		7.83	.222
1900	3		
06		7.10	.202
10	4		
15		7.30	.207
18		7.04	.200
20	3		
30	2		
35		3.84	.109
40	4		
43		5.54	.169
48		6.66	.189
50	3		
2000	1		
10	1	1.64	.047

Storm No.5 - Continuation

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
2020	1		
30	1		
38		.63	.018
40			
50			
2100			
02		.33	.009
10	1		
15		.82	.023
20			
30			
2132		.41	.012
2140			
50	1		
2200			
05		.13	.004
10			
20	1		
27		.20	.006
30	2		
40	2		
43		1.09	.031
50	1	1.17	.033
2300	2		
05	End	.89	.025
2322		.33	.009
2345		.18	.005

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)

Storm No.6 - Nov.14, 1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
0030	Start	.30	.009
36			
40	1		
50	1		
55			
0100			
04			
10			
20			
30			
37			
40			
50			
55		.03	.001
0200	1		
10			
20		.04	.001
30			
40	1		
41		.10	.003
50			
56		.43	.012
0300	1		
03		.43	.012
0310			
15		1.18	.034
20	2		
30	1		
40		.23	.007
50			
0400			
03		.11	.003
10	1		
11		.12	.003
20	1		
28		.60	.017
30			
33		.65	.018
40	1		
44		1.51	.043
50	2		
57		.58	.016
0500	1		
0508		.41	.012
10			
19		1.23	.035
20	1		
23		1.14	.032
30	1		
0532		1.23	.035
40	2		
42		7.10	.202
50	5	3.02	.086
58		2.14	.061
0600	1		
09		9.84	.279
10	2		
14		10.47	.297
19		9.39	.267
20	9		
23		6.47	.184
30	5	6.47	.184
37		4.19	.119
40	4		
50	1	1.68	.048
56		1.71	.049
0700	1		
09		0.70	.020
10			
20			
25		.28	.008
30			
40			
50			
0755		.11	.003
0800			
10			
20	1		
30		.13	.004
40			
41		.13	.004
50	1		
54		1.99	.057
0900	2		
07		.92	.026
10	1		

Storm No.6 - Continuation

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
0915		1.71	.049
20	2		
30	2		
38		1.45	.041
40	1		
47		1.81	.051
50	1		
1000	2	.77	.022
10	1		
15	End	.25	.007
20			
30			
40		.09	.003
1050			
1055		.06	.002
1100			
10			
20			
30		.08	.002

Storm No. 7 - Nov.15,1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
1130		.00	.000
35			
40		.20	.006
45			
50		2.00	.057
55			
56		2.00	.057
1200		1.39	.039
05			
10		.82	.023
15			
20		1.39	.039
25			
28		5.75	.163
30			
32		5.75	.163
35			
38		4.75	.135
40			
41		4.75	.135
43		5.87	.167
45			
47		5.87	.167
50			
1255			
58		3.29	.093
1300			
05			
10			
12		2.44	.069
15			
20		2.44	.069
25			
30		3.51	.100
35		2.85	.081
40			
45			
50			
52		6.47	.184
55			
1400			
05			
06		2.44	.069
10			
13		1.71	.049

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff (flow rate (m^3/s)
1415			
20			
21		1.54	.044
25		1.71	.049
1430			
33		4.24	.120
35			
36		4.24	.120
40			
45			
50			
52		2.44	.069
54		2.44	.069
55			
58		3.06	.087
1500		3.06	.087
05			
06		2.25	.064
08		2.25	.064
10			
15		2.85	.081
20			
23		2.85	.081
25			
30			
35			
40			
45			
50			
1552		.47	.013
55			
1600			
05			
10		.37	.011
15			
20			
25			
30			
35			
40			
45			
50			
55			
1700			
1730		.00	.000

Storm No.8 - Nov.28,1973

Time - hours and minutes	Raingauge tips (0.1" each)	Runoff flow rate (cfs)	Runoff flow rate (m^3/s)
0410	Start		
20	1		
30	1		
40			
50	1		
0500	1		
10			
20	1		
30	2		
40	1		
50	2		
0600			
10	1		
20	1		
30	1		
40			
50	1		
0700		.28	.008
10	1		
20	1		
30	1	.82	.023
38		1.17	.033
40	1	1.39	.039
47	1	9.54	.271
0750	9	9.17	.260
0758		3.29	.093
0800	1		
02		2.44	.069
03		2.25	.064
08		3.06	.087
10	3	3.06	.087
13		2.44	.069
20	1	1.09	.031
23		.82	.023
30		.47	.013
40		.33	.069
50			
56		.28	.008
0900	3	.58	.016
06		4.75	.135
10	5	7.76	.220
12		8.45	.240
20	4		
21		2.64	.075
23		2.64	.075
30	3	3.51	.100
38		5.02	.143
40	5	5.02	.143
42		4.24	.120
0948		2.44	.069
50	2		
57		.95	.027
1000	1	.95	.027
06		1.39	.039
10	1	1.39	.039
16		1.09	.031
19		1.09	.031
20	1		
25		2.64	.075
27		2.85	.081
30	3	2.25	.064
38		1.09	.031
40	1		
41		1.03	.029
47		1.09	.031
50	1		
51		.95	.027
1100		.58	.016
10	1		
17	End	.20	.006
30		.13	.004
1200		.07	.002